Comparison of Different Methods for the Estimation of Primary Stresses in Rock Salt Mass with Respect to Cavern Design

Kurt Staudtmeister[a] and Thomas Schmidt[b]

[a]Institut für Unterirdisches Bauen (IUB), Universitat Hannover, Weltengarten 1, 30167 Hannover, Germany

[b]EWE Aktiengesellschaft,
Tirpitzstr. 39, 26122 Oldenburg, Germany

From the rock mechanical point of view a most accurate knowledge of the magnitude of the primary stresses is of major importance for the design of caverns in rock salt mass. This fact has become more and more essential especially with reference to rock mechanical optimisation concepts for the layout of gas storage caverns. Here, the primary state of stress has a substantial influence on the maximum permissible internal cavern pressure within normal operation periods. Further, when investigating the post operation period abandoned cavern, the primary state of stress still is an essential parameter that has to be determined accurately. As has been shown by experience the assumption of standard average densities or fixed gradients for the salt rock mass as well as for the overlying rock mass may lead to remarkable deviations of the adopted primary stress state in the calculation model compared with the in situ situation.
For estimation the primary state of stress in: a salt dome four different procedures can be applied:

- determination of the densities as a result from geological interpretation
- evaluation of in situ pneumatic fracturing tests
- evaluation of in situ hydraulic fracturing tests and
- interpretation of borehole gravity measurements.

The simultaneous application of these different procedures in the framework of two gas storage projects provides the data base for a comparison, worked out in this publication. As a main result it will be shown that not only the accuracy of the measurements itself but also a proven competent interpretation is necessary.

1. INTRODUCTION AND BACKGROUND

Within the dimensioning of caverns in rock salt mass theoretical models have to be applied for the calculation of the state variables in the vicinity of the caverns. These state variables, for example stresses and strains are the basis for the determination of the operating conditions.
Most important input parameters for the calculation models are the material characteristics, the geometrical configuration and the loading of the system. For a given rock salt quality and a fixed geometry the optimisation has to be performed with the goal to obtain a safe and economical operation i.e. loading variables. For a cavern the loading results from the pressure difference between the primary stresses and the internal pressure conditions. Whereas the internal pressure versus time is result of the optimisation process, the primary stresses are a predetermined input value.

During the development of design concepts the knowledge of the complex stress strain behaviour of rock salt has improved as well as the capabilities of modelling detailed geometries and loadings. Of course these advanced methods require input data, as accurate as possible.
This requirement leads to a more detailed consideration of primary rock mass pressures. Instead of using general figures for gradients as, for example 1 psi/foot or standard densities for rock salt mass and overburden layers, recent projects showed the trend to assess the primary stresses in a more specific manner. The results of special investigations gave in several cases significant deviations from the standard assumptions.
The determination of the density of the rock salt mass can be carried out reasonably precisely in the laboratory. Core material of the rock salt section is available for the rock mechanical tests to characterise the material behaviour. In most cases however no cores were taken in the cover rock

section. The assessment of the cover rock densities however on the basis of the conventional borehole logs is in most cases associated with a certain amount of error.
Complementary methods to improve the figures of primary stresses are pneumatic or hydraulic fracturing. In these procedures suitable well intervals are sealed by packers and pressurised by means of a gaseous or liquid medium [1,2]. After initiating fracturing of the rock mass the system is closed and the pressure drop is measured versus time. Performing several re-fracs gives pressure curves, which are independent on the secondary stress field around the borehole. The free is assumed to open perpendicular to the smallest principal stress component. Analysing the pressure decrease gives a measure of the primary stress field, which will be discussed using an example later.
For the conditions of isotropic state of stresses in a salt massive, where the vertical stress component is assumed to be equal to the lithostatic rock mass pressure and horizontal components have the same value, borehole gravity measurements BHGM can be applied. The borehole gravity meter measures gravity while held stationary in a well bore. The vertical gradient of gravity in the well bore is directly related to the average density of the rock surrounding the well.
The gravity values recorded in the field are corrected for solar and lunar tides during recording. Additional corrections are necessary for drift and terrain variations. BHGM densities are influenced by changes in rock density associated with structures at considerable distances from the well. This influence increases with density contrast and volume and decreases with distance from the well. In the case of salt domes or pillows, there are generally higher density sediments overlying and surrounding the salt. To correct for the influence of the structure, a structural model is constructed using the main geological units.
For primary stress gradient determination in the rock mass a larger depth penetration offers a substantial advantage. Whereas with a gammagamma density probe one can assume some inches of penetration, the gravimeter is influenced by the rock mass in a much larger area surrounding the well. This means that inhomogeneities near the well can be detected and infiltration by mud and calibre variations are negligible [3].

2. COMPARISON OF THE DIFFERENT METHODS FOR A GAS CAVERN PROJECT

2.1 Project and basic measurement results

In the well Rüdersdorf K101 of EWE AG investigations with different methods had been carried out in 1998. The aim was to have a good estimation of the primary state of stresses in the range of the planned cavern. The location of the cavern is in a salt pillow. An isotropic primary state of stress can be assumed.
The cavern roof is intended at a depth of 1280 m, the sump at 1600 m. In detailed pneumatic fracturing tests at four different depths, hydraulic fracturing tests at two different depths and borehole gravimetry measurements (BHGM) down to 1280 in had been performed. The frac tests were carried out by UGS, Mittenwalde, the borehole gravity measurements were conducted by EDCON, Denver.
Figure 1 shows the so-called pressures at rest of the pneumatic fracturing tests in the four different investigation depths. As basis for the gradient in the rock salt mass a density of 2.17 t/m^3 was taken as start value. This density was derived by density determinations of core material as well as by BHGM and gives the gradient in the regression line in Figure 1.
In Figure 2 the relevant shut in pressures Psi of the hydraulic fracturing tests are illustrated for the two investigation depths.
Figure 3 shows the rock mass pressures for a depth of 1280 m derived from borehole gravity measurements as well as an upper and lower limit from an error estimation. The relevant line for the cavern region in this case runs through the measurement value for 1280 m depth.
From the assessment of the geological description the expected primary stresses at cavern depth are shown in Figure 4.
The quaternary has a thickness of 86 m and is followed by layers of shell lime and bunter sandstone. The top of the Staßfurt rock salt is situated at a depth of 875.5 m.

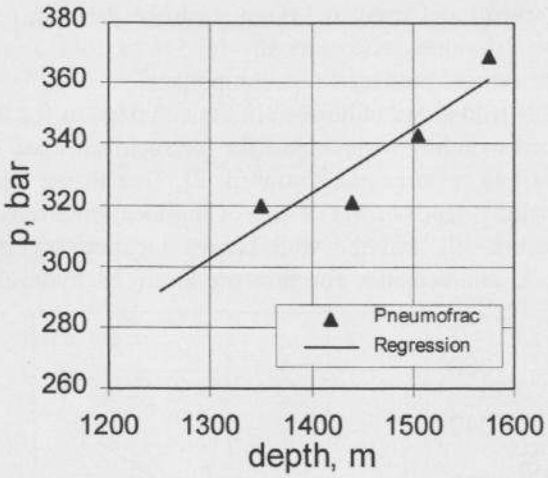

Figure1. Results of pneumatic fracturing tests

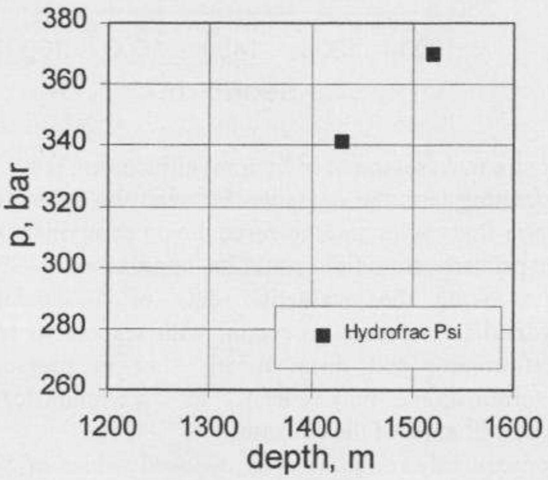

Figure 2. Results of hydraulic fracturing tests

Taking into account the depth of the last cemented casing at a depth of 1240 m in this case the fraction of the overburden is high compared to the thickness of the salt cover above the cavern. This\ fact consequently leads to different estimations about primary rock mass stress, because a certain range of rock mass densities has to be considered.

For the different layers according to table 1 the parameter combination (1) is a realistic estimation. The parameter combination (2) is a conservative estimation with respect to maximum cavern pressure determination.

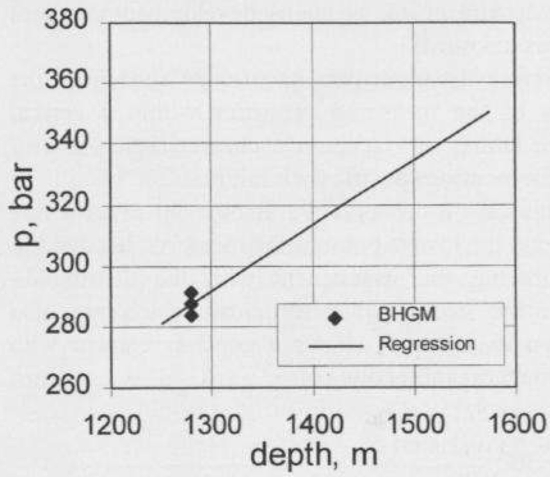

Figure 3. Results of BHGM measurements

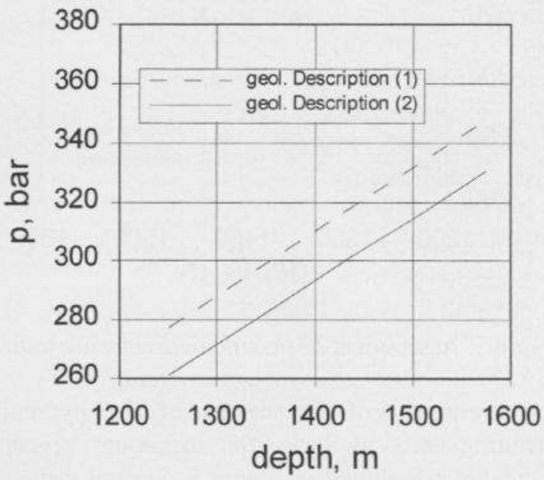

Figure 4. Range of assumed rock mass stress from geological description

The different parameter combinations for the density distribution in the well Rüdersdorf K101 are summarised quantitatively in table 1.

2.2 Assessment of the data with respect to maximum cavern pressure design

Figure 5 shows the evaluation of the results of the pneumatic fracturing tests with respect to the primary stresses as input data for the maximum pressure determination. The mechanisms of frac and time dependent frac geometry development are more or less unknown.

Therefore the input data have to be chosen on the basis of the measured pressures within a certain range taking into account a characteristic gradient for the location specific rock salt mass.

In this case a conservative assessment gives a line through the lowest point of the measured bandwidth. Comparing this assessment with the distribution from the geological description, which are also drawn in figure 5, shows a good agreement with parameter combination (1).

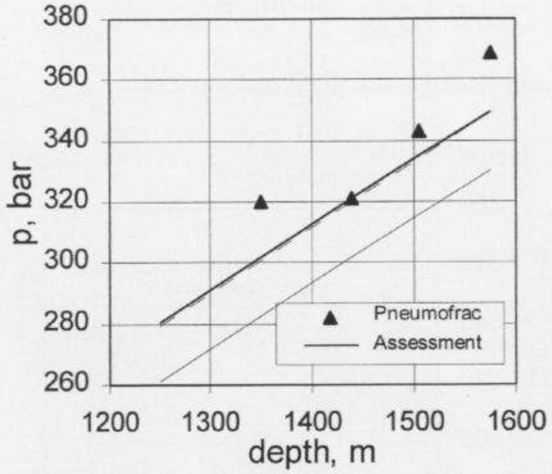

Figure 5. Assessment of pneumatic fracturing tests

The evaluation of the results of the hydraulic fracturing tests as basis for maximum pressure calculations is shown in Figure 6. Several different methods can be applied for the determination of the instantaneous shut in pressure Psi [4].

From the experience of the evaluation of hydraulic fracturing tests in the locations Etzel, Krumhörn, Reckrod and Bremen Lesum it can be derived, that the Psi-values systematically lie 5% to 10% above the vertical primary stress component.

This tendency can be seen in the comparison for the corresponding components for the rock salt mass of the gas cavern field Krumhrn [2]. Due to the very shallow depth of top of salt of the location Bremen Lesum 301 and the well known location specific rock salt densities for this site from 18 hydraulic

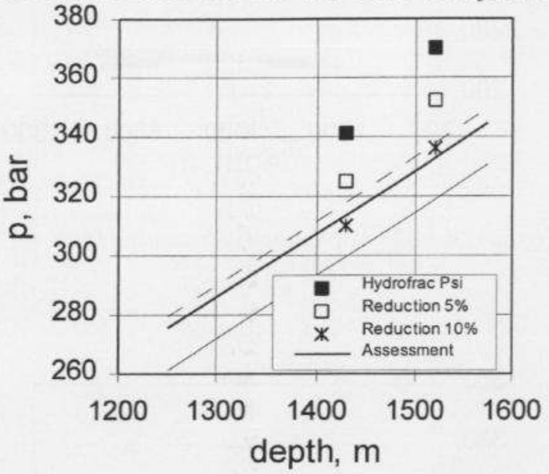

Figure 6. Assessment of hydraulic fracturing tests

fracturing tests the deviation between the values of the re-frac cycles and the vertical Non component of the primary stress field could be approximately 9%. Just taking the evaluation data of a standard hydraulic fracturing procedure with respect to test performance and instantaneous shut in pressure determination may lead to a significant overestimation of the densities.

Consequently in Figure 6 the reduced values of 5% estimation from the results of the two measuring

Table 1 Assumed density combinations from geological description of well Rüdersdorf K 101

depth interval		densities (1)	densities (2)
m		t/M3	t/M3
0-86	Quartemary	2,00	1,80
-286	Shell Lime	2,50	2,20
-445,5	Upper Bunter Sandstone	2,20	2,00
-622,6	Middle / Lower Bunter Sandstone	2,40	2,20
-830,6	Rock Salt / Anhydrite / Salt Clay	2,30	2,18
-875,5	Potash Seam Staßfart	2,15	2 ' 10
-final depth	Sta13furt - Rock Salt	2,20	2,17

depths the reduction of 10% seems to be reasonable and leads to the shown assessment line.
Again comparing this assessment with the distribution from geological description shows a good agreement with parameter combination (1).
From experience with borehole gravimetry measurement in the gas cavern field Ll. Torup, Denmark, and Nüttermoor, Germany, which gave good agreement with geological interpretation and density estimations from rock samples and log interpretation, the primary stresses for maximum pressure determination according to Figure 7 is chosen, situated at the lower border of the error estimation bandwidth.
The bandwidth contains error considerations for errors in depth measurements, in terrain corrections and in structural corrections. For the structural corrections reasonable initial densities are assigned to these formations and the resultant BHGM density is calculated for the model at the survey measurement positions. These model BHGM densities are then compared to the corrected field BHGM densities. The density values assigned the geological units are then iterated until a match is obtained between the model calculated density and the corrected field BHGM density.

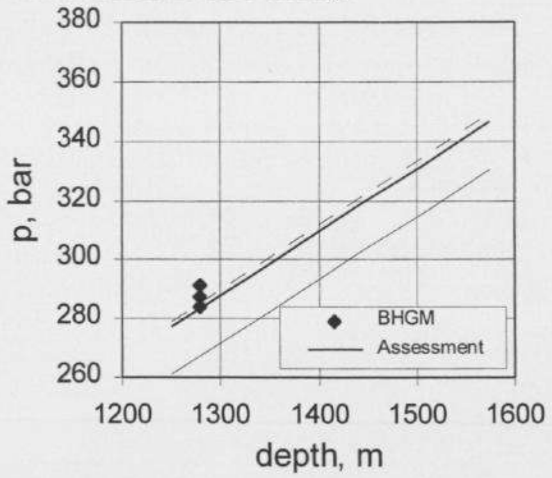

Figure 7. Assessment of borehole gravimery tests

The comparison of the assessment line with the distribution from geological description is resulting again in a good agreement with parameter combination (1) from geological interpretation.
The analysis of measurements and[evaluations within the framework of the extension of the gas cavern field Huntorf shows very similar results.

3. CONCLUSIONS

It is evident from the assessment considerations, that with the experience of several projects all the different methods can give a good estimation of the primary state of stresses in the rock salt mass. For all methods a good agreement with a realistic density distribution according to the geologic description in parameter combination (1) can be stated.
Without an additional verification by in situ measurements however the determination of primary stresses would have required a parameter description according to parameter combination (2), which consequently results in lower recommended maximum pressures for the operation of the gas cavern.
For the example shown in section 2 the difference in the primary stress field assumption for maximum pressure determination is roughly 20 bar at depth of last cemented casing.
Here the more detailed knowledge of additional measurement assessment can lead to an increase of maximum pressure of more than 15 bar, which gives a considerable increase in working gas volume.

REFERENCES

1. S. Forster and G. Japel, Well Hole Test Method for the Determination of the Minimum Principal Stress in Rock Salt as a Basic Value for Submitting Maximum Permissible Operating Pressures on Gas Caverns, Proc. of the Int. Conf. On Storage of Gases in Rock Caverns, Trondheim, 1989.

2. F. Rummel,., K. Benke and H. Denzau, Hydraulic Fracturing Measurements in the Krummh6m Gas Storage Field, Northwestern Germany. Meeting papers of SMRI Spring Meeting, Houston, 1996.

3. S. Folle and 0. Rolfs, Gravimetry to Determine Rock Density, Int. Conf. on Underground Gas Storage, Moscow, 1995.

4. F. Guo, N.R. Morgenstern and J.D. Scott, Interpretation of Hydraulic Fracturing Presssure: A Comparison of Eight Methods Used to Identify Shut-In Pressure. Int. Journ. Rock Mech. Sci, Vol. 3 0, No. 6, 1993.